Dynamics and Control of Underwater Gliding

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LONG-TERM GOALS

My long-term goal is to help improve versatility of underwater gliders as platforms for ocean sampling and other applications by contributing to the development of a methodology for designing and analyzing high-performance, cost-effective underwater glider controllers.

OBJECTIVES

I am interested in establishing a framework for studying dynamics and control of underwater gliders. The focus is on dedicated gliding vehicles that have the ability to change mass (or volume) for buoyancy control and to redistribute mass for attitude control. The framework consists of a dynamical systems model of underwater gliding vehicles together with techniques for generating and controlling glide maneuvers in the presence of uncertainty. The first objective is the development of a model that is representative of a general class of underwater gliders. The second objective is an analysis of dynamics and stability of the dynamic glider model. The third objective is the development of control laws for stabilizing individual glide motions, e.g., straight-line or spiral glide paths, and for performing maneuvers, following waypoints and tracking trajectories. A further objective is the development of methodology for assigning performance measures and then to optimize vehicle control design with respect to these measures. Finally, it is of interest to address problems in coordinating control for a network of underwater gliders.

APPROACH

The approach is to develop a low-dimensional model of glider dynamics both for analysis of dynamics and stability and for model-based feedback control design. We are using theory, analysis, simulation and laboratory-scale experimentation in this project. Modelling is based on rigid body dynamics of the glider with a dynamic model of varying mass and mass distribution, potential flow models of the fluid to capture buoyancy effects and semi-empirical modelling of lift and drag. For the model we assume a glider with simple body and wing shape. Control is applied to two point masses inside the vehicle: the first point mass has variable mass but fixed position while the second point mass has fixed mass but variable position relative to the center of buoyancy. One control input changes the mass of the stationary point and another control input vector corresponds to the force applied to the movable mass. The model describes the nonlinear coupling between the vehicle and the shifting and changing mass.

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14. ABSTRACT

My long-term goal is to help improve versatility of underwater gliders as platforms for ocean sampling and other applications by contributing to the development of a methodology for designing and analyzing high-performance, cost-effective underwater glider controllers.

15. SUBJECT TERMS

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Our model-based, feedback control design methodology is intended to improve upon the currently implemented glider control strategies. A systematic design methodology that provides control in the full state-space is expected to make it possible to design glider controllers that require less experimentation and tuning and provide more robustness to fouling, payload changes and other uncertainties as compared to current techniques. Additionally, with a model-based approach, a dynamic observer can be designed to estimate states such as glider velocity. These estimated states can then be used to determine horizontal glider motion instead of the current methods which rely on assumptions of constant angle of attack. A model-based approach is also being used in determining optimal glider motions.

Methods from mechanics and dynamical systems theory for checking stability and for analyzing dynamics are being applied. Both linear control theory and nonlinear control theory are considered to first stabilize individual glide maneuvers and then to join them together for path following. Optimal control theory is being used to come up with paths and control laws that are energy and time efficient. Simulation tools include MATLAB, Mathematica, as well as a 3-D interactive graphics simulation platform that we are developing. We are also making use of a small (laboratory-scale), experimental underwater gliding vehicle that we have built and are continuing to develop in our laboratory.

Artificial potentials are a central idea in the approach to developing coordinated control strategies for multiple underwater vehicles where the goal is to use decentralized control laws to effect desired vehicle schooling patterns and to enable adaptive group decision making in sampling and gradient following schemes. Potentials are used to maintain formations with specified vehicle spacing and velocity alignment. Potentials are also used to direct the group as a whole and to change the formation. The motivation for this approach comes from observations of schooling fish of simple local traffic rules at the individual level leading to emergent intelligence at the group level. The local traffic rules make use of measurements of the behavior of near neighbors.

Key individuals who are working with me at Princeton on this and related work include two graduate students (J. Graver, P. Bhatta) working on the gliding modelling, dynamics and control laws, another former graduate student (C. Woolsey) now Assistant Professor the Dept. of Aerospace and Ocean Engineering at Virginia Tech who has worked primarily on a related problem of controlling and underwater vehicle using internal rotors, a former post-doc (M. Chyba) now at U.C. Santa Cruz who works on optimal control and a technician (R. Sorenson) who works on the vehicle. Additional there are two graduate students (E. Fiorelli and T. Smith) who are studying the problem of designing coordinating control laws for multiple underwater vehicles and a post-doc (R. Bachmayer) who is working to develop a multiple-vehicle testbed in a freshwater tank at Princeton and who is working on the problem of networked vehicles for gradient climbing.

WORK COMPLETED

We have derived a 3-D nonlinear dynamic model of a buoyancy-propelled, fixed-wing glider with attitude controlled by means of active internal mass redistribution. The model includes hydrodynamic forces and coupling between the vehicle and the movable and changing internal mass. The model has been specialized to the vertical plane. For the vertical plane restriction, we have derived expressions for steady glide paths as a function of desired glide path angle and glide path speed. Conditions for feasibility of glide paths are included.

We have studied stability of the steady glides. We have studied controllability of steady glide paths in the case that the internal movable mass has two degrees of freedom and in the case that it has only one degree of freedom. We have also studied observability given assuming various typical sensor suites.

We have derived linear optimal feedback control laws to stabilize steady glide paths in the vertical plane. These control laws take into account the limitations on position and velocity of internal movable mass. We have also derived optimal observers to estimate states not directly measured with typically available sensors. The methodology has been applied to a model of our own laboratory-scale underwater glider.

We are investigating the utility of a simplified dynamic glider model. This simplified glider model has lower dimension because the dynamics associated with the moving internal mass and changing ballast are neglected. Instead, the changing buoyancy is replaced with a control force pointing along the direction of gravity. The moving CG position is replaced with a control torque about a line perpendicular to the direction of gravity. The hydrodynamic forces and the remaining rigid body forces are all retained.

This model will allow us to isolate and understand the role of the lifting surfaces on a rigid body in the water. Together with the higher-dimensional model, it will allow us to isolate the role of the moving mass and changing ballast on the dynamics and stability of an underwater glider. The simplified model will also be useful as a stepping stone in deriving nonlinear control laws for glider stabilization and tracking. Theory has also been developed for time-optimal control of mechanical systems and using this simplified model it has been applied to underwater gliders. Simulations in MATLAB and a 3-D graphical simulation of an underwater glider have been developed.

We have developed a framework for design of coordinating control laws for multiple autonomous underwater vehicles. Control forces and torques are derived from artificial potentials intended to maintain desired spacing of vehicles and to keep the vehicles aligned. In concert with this framework we have developed strategies for a group of vehicles to cooperatively perform gradient climbing.

Our laboratory-scale freshwater underwater glider has been upgraded and testing of this new glider ROGUE (Remotely Operate Gliding Underwater Experiment) has been initiated. We have a new, indoor freshwater tank for testing of underwater vehicles. The tank is 21 feet in diameter and 8 feet deep. This tank is part of the multiple-AUV testbed under development.

RESULTS

We have an analytic model of the dynamics of a generic underwater glider with which we can study the fundamentals of glider stability, dynamics and control. In particular we are able to study the nonlinear coupling between the vehicle body and the internal moving mass. We have been able to show linear controllability even in limited circumstances as well as linear observability even with a limited number of sensor. This type of controllability allows not only for useful linear control design but also provides a good indication that many nonlinear control techniques will be applicable. Using the observability feature of the dynamics we have been able to demonstrate the potential for effective state estimation. Use of dynamic estimates of states can improve upon current practice in which certain dynamic variables are assumed constant for the purpose of designing feedback control.

Large regions of attraction have been demonstrated for steady glide paths in the vertical plane using linear control. However, linear control does not seem to be sufficient to effect switches from upward pointing glide paths to downward pointing glide paths (and vice-versa). We are currently investigating complementing linear feedback control with a feed-forward term as well as using nonlinear control design methods.

Artificial potentials are proving to be an effective way to establish interaction rules between vehicles moving in a group so that we can perform tasks such as gradient climbing efficiently and robustly. The framework gives us the important advantage of adaptation and real-time decision making by the group in response to distributed measurements (across the group) of the underwater environment.

IMPACT/APPLICATIONS

In relation to existing methods of ocean sampling, autonomous underwater gliders offer a host of technical advantages: superior spatial and temporal measurement density, longer duration missions and greater operational flexibility. These advantages are expected to be greatest when multiple gliders are operated cooperatively in a network. With effective control design it is possible that networks of vehicles can achieve highly efficient and adaptive group capabilities from simple rules at the individual vehicle level, much like emergent intelligence in schools of fish. This could lead to improved data-processing and decision-making capabilities which could have a major impact on missions such as adaptive ocean sampling. Our work on robust control of individual underwater gliders and coordinating control of networks of underwater vehicles is a contribution to the methodology necessary to realize this vision.

Additionally, the deeper understanding of the consequences and opportunities afforded by using internal actuation, in particular using mass distribution but also using rotating masses (i.e., internal rotors) may have implications in a wide variety of vehicle applications.

TRANSITIONS

We have begun discussions with R. Light at University of Washington on applying our modelling approach to Seaglider. We have begun discussions with personnel at the Woods Hole Oceanographic Institution (D. Fratantoni) and at Rutgers University (S. Glenn) about using our controllers on experiments at sea with networks of (SLOCUM) gliders.

RELATED PROJECTS

I participate in an NSF/KDI funded project joint with A.S. Morse (Yale), P. Belhumeur (Yale), R. Brockett (Harvard), D. Grunbaum (U. Washington) and J. Parrish (U. Washington) on coordination of natural and man-made groups. We are studying schooling of fish and “schooling” of autonomous underwater vehicles. Control theory and a multiple-vehicle experimental testbed are being developed at Princeton. This project is related to the problem of coordination of groups of underwater gliders.

I have a new AFOSR funded project on Coordinated Control of Groups of Vehicles. This is a joint project with Vijay Kumar and James Ostrowski at University of Pennsylvania. A focus of the project is understanding cooperation in the context of coordinated control of distributed, autonomous agents, and the collection and fusion of the sensor information that they retrieve.

With my colleague Edward Belbruno, I have worked on a project for Global Aerospace Corporation (funded by NASA) on low-energy trajectory control of a stratospheric balloon network. The objective is to manage the geometry of the constellation of balloons for science and communication applications in the presence of a non-uniform flow field at 35 km altitude. The balloons can be controlled in a limited way with sails. This project is related to the problem of coordination of groups of underwater gliders introducing the specific problem of coping with a non-uniform flow field.

I am working on controlling autonomous underwater vehicles with internal actuation, namely internal rotors, as part of a project on stabilization of mechanical systems using controlled Lagrangians. This is a joint project with A.M. Bloch (U. Michigan) and J.E. Marsden (Caltech).

PUBLICATIONS

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